Interband calibration of the POLDER sensor

Mbarek Asmami, Lucien Wald

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M.Asmami & L.Wald
Centre d'Energétique, Groupe Télédétection & Modélisation, Ecole des Mines de Paris, Sophia-Antipolis, France

ABSTRACT: The interband calibration is the transfer of the absolute calibration from one or two wavelengths to the other spectral bands. This is done by adjusting the spectral reflectances observed over natural some targets, which present spectrally flat reflectances in the solar spectrum, to the calibrated reflectance for the same target. Cloud and the ocean sunglint are such bodies. The two phenomena are very frequent in satellite imagery and are certainly good condidates for an operational procedure. This paper describes two approachs, which are applied to the PolDER "**Pol**arization and **D**irectionality of **E**arth's **R**eflectances" spectral bands using these targets.

The accurate calibration of the Earth observation systems in space is now recognized as a major component of the quality of an image (see e.g. Abel 1990). The efficiency of the utilization of remote sensing data by the scientific community for the study of the global changes or by private bodies for land management and other purposes is directly related to the performances of the calibration procedures. Satellite sensors in the solar spectrum are very difficult to calibrate due to the lack of reliable on-board calibration devices. The preflight calibrations are subject to change due to the hostile environment of the sensor: outgasing, deterioration in the optronic system, variation in the spectral filter characteristics, ... Engineering responses have been brought up to this problem. Some are dealing with very sophisticated on-board calibration devices with the following drawbacks: increase in complexity, increase in weight, more demand in energy, increase in cost, possible decrease in reliability of the total system. The Earth viewing calibration approach has been recently developped as a backup solution to the possible failure or unreliability of on-board calibration devices. It is based upon the knowledge of physical characteristics of some Earth phenomena as well as upon the processing of the digital imagery flowing down from the sensor itself (Koepke 1982, 1983; Fraser, Kaufman 1986; Frouin, Gautier 1987; Price 1987, 1988, 1989; Paris, Justus 1988; Teillet *et al.* 1988, 1990; Holben *et al.* 1990; Brest, Rossow 1990; Kaufman, Holben 1990; Santer et *al* 1990). It has also been proposed as an alternative to the on-board calibration devices for the monitoring of the post-launch calibration. Such an approach has the following advantages: decrease in complexity and weight, less energy consumption, decrease in cost. Each type of approach may be phased from time to time with on-ground radiometric measurements or perfectly calibrated airborne measurements (Begni *et al.* 1986; Hovis, Knoll 1985; Smith *et al.* 1988; Gu *et al.* 1990; Hill 1990).

The radiometer PolDER (**Pol**arization and **D**irectionality of **E**arth's **R**eflectances) is to be built by Centre National d'Etudes Spatiales (CNES) and to be flown aboard the japanese platform ADEOS. This radiometer is one of the many French contributions to the world efforts for the comprehension of the global changes. Table 1 presents the spectral bands of PolDER as compared to those of AVHRR and SPOT. PolDER offer a series of oblique views, aft to fore. Its pixel size is 6-7 km while it is 1 km for AVHRR and 20 m for HRV.

Among other applications, PolDER intends to be a breakthrough in ocean colour studies. As such, its data must be very accurately calibrated. The nominal requirement is an accuracy better than 0.01 in reflectance in each spectral band. PolDER will not contain any calibration on-board device. Once the preflight calibration done, the calibration will be continuously monitored and corrected by analyzing digital imagery over particular sites on the Earth.

The radiometric model of PolDER is very sophisticated because of the bi-dimensional aspects of the wide field-of-view electronically scanning sensor and because of the polarization measurements (Martinuzzi 1991). Briefly speaking, the calibration is composed of an absolute calibration term and of correction terms related to variations pixel to pixel (high spatial frequencies) and to variations at low spatial frequencies for polarized and unpolarized measurements. The monitoring of the variation of

Table 1. Spectral bands for PolDER, AVHRR and SPOT-HRV. The letter P stands for polarization.

443 (P)		
490		HRV1
565		
665 (P)	AVHRR 1	HRV2
762		HRV3
765		
865 (P)	AVHRR 2	
910		

each term during the sensor lifetime is entirely done by analyzing digital imagery over particular sites on the Earth.

Over the ocean, out of the glint direction, at very oblique viewing angles, a major part of the radiance observed at satellite level originates from molecular scattering that is practically invariant in time and space. It depends only on the atmospheric pressure and is given by the Rayleigh's law. The rest is due to aerosol scattering and radiance coming from the sea (interior or surface). It is expected that under certain conditions, the reflectance at satellite level can be estimated using a numerical model, with an absolute accuracy of 0.01 for the smallest wavelengths (443 or 490 nm). The absolute calibration for the other spectral bands is then obtained by what is called the interband calibration, which is the transfer of the absolute calibration for 490 nm (or 443 nm) to the other wavelengths. Some Earth's bodies present spectrally flat reflectances in the solar spectrum. The transfer of calibration is done by adjusting the spectral reflectances observed over these targets to the calibrated reflectance for the same target. Clouds and ocean sunglint are such bodies and are the subject of the present study. They are very frequent in satellite imagery and are certainly good candidates for an operational procedure.

If ρ_λ denotes the actual reflectance at satellite level, $\rho_\lambda{}^{sat}$ the calibrated reflectance output from the sensor, and γ_λ the correction factor to account for variations in absolute calibration, then:

$$\rho_\lambda = \gamma_\lambda \, \rho_\lambda{}^{sat} \tag{1}$$

and

$$R(\lambda,\lambda_0) = \rho_\lambda / \rho_{\lambda 0} = (\gamma_\lambda \, \rho_\lambda{}^{sat}) / (\gamma_{\lambda 0} \, \rho_{\lambda 0}{}^{sat}) \tag{2}$$

where the subscript 0 denotes a spectral band which absolute calibration is known and hence $\gamma_{\lambda 0}$. Over spectrally constant bodies, the ratio of the reflectances should be equal to 1:

$$R(\lambda,\lambda_0) = \rho_\lambda / \rho_{\lambda 0} = 1$$
$$\Rightarrow \gamma_\lambda = (\gamma_{\lambda 0} \, \rho_{\lambda 0}{}^{sat}) / \rho_\lambda{}^{sat} \tag{3}$$

Indeed, the reflectance observed at satellite level over spectrally constant bodies is not strictly equal to 1 but close to 1, mostly because of the influence of the atmosphere. The interband calibration requirements for PolDER implies that the ratio $R(\lambda,\lambda_0)$ may fluctuate within $\pm$ 0.01 around a known constant.

INTERBAND CALIBRATION WITH CLOUDS AS TARGETS

The very reflectance of the cloud is spectrally constant in most of the solar spectrum and therefore clouds are good candidates for the interband calibration. Such a property is often used in procedures for cloud detection (see e.g. Saunders 1986; Saunders, Kriebel 1988; Wald *et al.* 1991). Moreover clouds are very frequent in satellite imagery and this renders an operational procedure possible.

At satellite level, the reflectance observed over a cloud is a function of the very reflectance of the cloud, the albedo of the underlying surface, the water vapour distribution of the environment in which the cloud is located, the clear-sky layer above the clouds in which molecular and particle scattering take place, and gaseous transmittance. If the reflectance of the ground is large enough with respect to the optical depth of the cloud, some of the spectral variations in reflectance observed at satellite level are due to the spectral variations of the ground reflectance. Also multiple reflections between the ground surface and a highly reflective cloud base may become important. Such cases must be avoided and only clouds over ocean areas will be examined, out of the sunglint area. However all the simulations have been done with two values of albedo, 0 and 0.1, in order to provide estimates of the errors one can expect if some clouds are partly covering the glitter area.

From the above considerations, it appears feasible to use reflectances observed at satellite level over clouds for interband calibration, at least for the spectral bands not located in oxygen water vapour absorption windows. Reflectances have to be corrected for ozone absorption if necessary. The decrease of the atmospheric diffuse reflectances as the wavelength increases is somewhat balanced by the increase of the diffuse transmittance and of the cloud reflectance. Water vapour absorption is not negligible at 865 nm and helps maintening the reflectance to a more or less constant level.

Quantitative estimates of the error budget are made using the model of Paris, Justus. This radiative transfer model consists of two clear layers sandwiching a plane-parallel cloud layer. Clear-sky optical effects are treated with modified Beer - Bouguer - Lambert's law relationships and cloud optical effects are treated with the delta-Eddington method. It is fully described in Justus, Paris (1987), Paris, Justus (1988) and Justus (1989). This model does not provide bi-directional reflectances and the

Table 2. Values taken by the various input parameters in the Justus, Paris model.

Parameters	Values
optical depth of the cloud	20, 30, 50, 70, 100, 150
cloud bottom altitude (km)	1, 2, 5
cloud top height (km)	2, 3, 4, 5, 7, 10, 12
granulometry of the cloud	five kinds
solar zenithal angle (degrees)	30, 60
type of atmosphere	Tropic, Midwin, Midsum, US62
aerosols type	maritime, continental
visibility (km)	23
ground albedo	0, 0.1
sensor filters	PolDER (8 channels)

Table 3. Ratios of reflectance given by the Justus, Paris model for PolDER case. Sun zenith angle is 30 °. Visibility is 23 km, maritime aerosol with 70 % humidity. Ocean albedo is 0. Reflectances at 565 and 665 nm have been corrected for ozone absorption, as well as the reflectances at 443 and 490 nm but only for the ratio 443 / 490.

ratio	opt. depth: 20 and top height: 2 km			opt. depth: 70 and top height: 7 km		
	midsum	midwin	tropic	midsum	midwin	tropic
443 / 490	1.01	1.01	1.01	1.01	1.01	**1.00**
565 / 490	.99	.99	.99	.99	.99	**1.00**
665 / 490	**1.00**	**1.00**	**1.00**	1.01	1.01	1.01
865 / 490	**1.00**	1.01	.99	1.01	1.02	1.01
565 / 443	.96	.96	.97	.98	.98	.99
762 / 765	.58	.57	.58	.65	.66	.65
865 / 665	1.01	1.01	**1.00**	**1.00**	1.01	**1.00**
865 / 910	1.36	1.16	1.44	1.24	1.10	1.30

outputs are albedos. These albedos are equal to the reflectances observed at satellite level for vertical sighting of the scene.

The intra-angular calibration of PolDER is taken into account by other means and here only nadir viewing may be considered. However attention has been paid to the influence of the viewing angle on the ratios. The reflectance of the cloud may be seen as a function of the sun zenithal angle, the viewing angle and the optical thickness defined for a vertical path. As cloud thickness increases, the original direction of the incoming beam is lost due to multiple scattering events and the reflectance of the cloud tends towards isotropy. A simple model (Eq. 8 in King *et al.* 1990) indicates that for the wavelengths 503, 673, 744 and 866 nm, the variation in reflectance with the viewing angle decreases as the optical thickness increases but still amounts to about 2 % for an optical thickness of 100 and across the field of view of PolDER. However, the ratios of the reflectances at these wavelengths to the reflectance at 503 nm do not vary in an appreciable way with the viewing angle, even for weak optical depth. Hence the influence of the viewing angle on the interband calibration is negligible.

The Paris, Justus model has been ran for various combinations of the input parameters (see table 2). Since this model defines an atmosphere by the ozone and water vapour contents, the air temperature at ground level and its lapse rate, the pressures at ground level and tropopause, some modifications of the typical values given for each standard atmosphere are possible. The influence of the error in measuring ozone upon the interband calibration can thus be assessed for example. The spectral filters for PolDER have been estimated from the gauges given in Martinuzzi (1991).

It appears that with respect to the scope of the study, the most important among the various parameters are the optical depth and the altitudes of the base and top of the cloud. Under reasonable conditions, some clouds may serve as targets for interband calibration of some of the spectral bands and fully meet the requirements of PolDER (table 3). These conditions vary from one spectral band to the other. The clouds must have an optical depth greater than 50, and the altitude of their top must be at least at 7 km, but lower and thinner clouds are preferable for some wavelengths. Sun must be as high as possible and clouds in tropical atmosphere give the best results.

Too much reflective clouds (*i.e.* very large optical depths) are not suitable.

The ratio (443 / 490) is often close to the upper limit of 1.01. This ratio decreases as the height of the cloud top increases. If these reflectances are corrected for ozone absorption, the ratio is closer to 1.00. A variation of 10 % in the ozone content, a typical measurement error, induces a negligible error of 0.001 of the ratio. For interband calibration, thick, high tropical clouds are preferable.

The spectral bands 565 nm and 665 nm must be corrected for ozone absorption. In that case, the ratios (565 / 490) and (665 / 490) are very close to 1.0, the ratio (565 / 443) being a bit lower than 1.00. A variation of 10 % in the ozone content induces an error of 0.006 of the ratio at 565 nm and 0.003 at 665 nm. While negligible at 665 nm, the error is not at 565 nm.

The ratio (865 / 490) is usually greater than 1.0. It increases as the cloud top height increases but still meet the requirements. The ratio (865 / 665) is very close to 1.0 once the latter corrected for ozone.

The ratios (762 / 490), (765 / 490), (762 / 765) are very dependent of the cloud top height and the 762 nm and 765 nm bands cannot be calibrated using clouds as a reference target. The 910 nm band is subject to water vapour absorption and cannot be calibrated using clouds as a reference target, too.

To summarize, it can be concluded that the clouds are suitable to transfer the absolute calibration from the 490 nm band to the 443 nm, 565 nm, 665 nm and 865 nm bands.

INTERBAND CALIBRATION WITH OCEAN SUNGLINT AS A TARGET

The albedo of the ocean is very low and the sea often appears as a dark body in satellite imagery taken in the solar spectrum. Under some observations conditions, called the specular reflection conditions, part of the solar radiation impinging the sea surface may be reflected towards the sensor. This part of the ocean appears very bright and is called the glitter area. It roughly has the shape of concentrical ellipses of decreasing intensity. The brightest point is the specular point and is the center of the glitter. The glint radiance is spectrally independent in the solar spectrum and its magnitude depends upon many factors such as the relative geometry of the system sun - pixel - sensor, the wind vector and its time variability, the wavelets spatial distribution, the fetch, the salinity, the stability of the air above the sea, the occurence of foam and its reflectance, both being also a function of the above cited parameters. The reflectance of the glint area decreases from the specular point outwards. The glitter angular width depends mostly upon the wind speed. The weaker the wind, the brighter the specular point and the sharper the glitter area (see e. g. Wald, Monget 1983).

The spectral independance of the reflectance observed over the glitter area makes this area a good candidate as a reference body for the interband calibration. The reflectance observed by the spaceborne sensor is composed of the glitter reflectance, underwater reflectance and diffuse reflectance. The diffuse reflectance originates from various sources : reflection of the skylight on the sea surface, scattering in the atmosphere by molecules and aerosols. Only the glitter reflectance is spectrally independent. Neglecting the multiple interactions between the sea surface and the lower layers of the atmosphere and neglecting the gaseous absorption for sake of simplicity, the reflectance measured at the satellite level $\rho_\lambda{}^*$ is:

$$\rho_\lambda{}^* = \rho_m + \rho_a + (\rho_g + \rho_w + \rho_f)\, e^{-\tau(1/\mu_s + 1/\mu_v)} \quad \textbf{(4)}$$

where ρ_m : reflectance due to molecular scattering,

ρ_a : reflectance due to aerosols scattering,

ρ_g : glitter reflectance,

ρ_w : underwater reflectance,

ρ_f : foam reflectance,

τ : $\tau_m + \tau_a$, optical depths of the molecules and the aerosols,

μ_s, μ_v : cosines of the sun and sensor zenith angles.

For low wind speeds (no foam), no aerosols and neglecting the water-leaving reflectance, the above equation becomes:

$$\rho_\lambda{}^* = \rho_m + \rho_g\, e^{-\tau_m(1/\mu_s + 1/\mu_v)} \quad \textbf{(5)}$$

Because of the spectral variations of the various terms in Eq. 4 (or even in Eq. 5), the interband calibration requirements can be met only if the glitter reflectance is far larger than the other reflectances. Using typical values from previous works (Herman *et al.* 1991; Kaufman, Holben 1990), the relative importance of the glitter reflectance to the atmospheric contribution is:

$$\rho_g / \rho_m \sim 0.2 / 0.05 \sim 4 \quad \textbf{(6)}$$

Herman *et al.* show that the spectral variation of the atmospheric contribution cannot be neglected. They observe from numerical simulations that $R(\lambda,\lambda_0)$ computed from $\rho_\lambda{}^*$ is close to 1 but with variations of order of 0.1, far from the requirements of 0.01. It can be concluded that a straightforward use of the reflectance observed at satellite level over the ocean sunglint does not provide an accuracy good enough for PolDER requirements.

An alternative way is to use the fact that the typical spatial scales within the atmosphere are greater than those of the ocean sunglint. Such an approach has been successfully used by Wald, Monget (1983) to assess the wind speed from sunglint observations in AVHRR imagery. From Eq. 5, the variation in space of the reflectance is:

$$\nabla\rho_\lambda^* = \nabla\rho_m + \nabla(\rho_g\, e^{-\tau_m(1/\mu_s + 1/\mu_v)}) \qquad (7)$$

Let be a low wind speed (2-3 m/s) which leads to a very sharp glitter area. Let the extremities of the segment for which the gradient is computed, be a few tens of kilometers apart, one being in the glitter area and the other outside. The extremity within the sunglint should be one of the brightest pixels but saturation of the signal level should be avoided. Along this segment, the air mass is roughly constant and the contribution of the atmosphere to the total reflectance should be close to a constant. On the contrary the variation in glitter reflectance is very large. The relative importance of the gradient of the glitter reflectance to the gradient of the atmospheric contribution is typically:

$$\nabla\rho_g / \nabla\rho_m \sim 0.2 / 0.01 \sim 20 \qquad (8)$$

If the gradient of reflectance observed at satellite level is spectrally constant, the correction factor γ_λ can be estimated:

$$R_\nabla(\lambda,\lambda_0) = \nabla\rho_\lambda / \nabla\rho_{\lambda 0} = 1 = \gamma_\lambda\, \nabla\rho_\lambda{}^{sat} / \gamma_{\lambda 0}\, \rho_{\lambda 0}{}^{sat}$$
$$\Rightarrow \gamma_\lambda = (\gamma_{\lambda 0}\, \nabla\rho_{\lambda 0}{}^{sat}) / \nabla\rho_\lambda{}^{sat} \qquad (9)$$

This approach minimizes the role of the atmosphere and should provide a spectrally constant quantity to calibrate each band relatively to a reference band. Such wind conditions are very frequent. Furthermore whitecaps usually appear for larger wind speed and therefore our lack of knowledge about their spectral reflectance is no longer a constraint.

The relative accuracy from pixel to pixel, *i.e.* the multiangular calibration (from CCD to CCD), must be taken into account. Nominal values are 0.001 for locations ten CCDs apart (*i.e.* about 70 km) and should not influence this method.

More exactly, it can be written from the above equations:

$$\nabla\rho_\lambda^* = \nabla(\rho_m + \rho_a) + \nabla(\rho_g)\, e^{-\tau(1/\mu_s + 1/\mu_v)} + \rho_g\, \nabla(e^{-\tau(1/\mu_s + 1/\mu_v)}) \qquad (10)$$

Because the glitter contribution is much larger than the atmospheric one, it comes:

$$\nabla\rho_\lambda^* \approx \nabla(\rho_g)\, e^{-\tau(1/\mu_s + 1/\mu_v)} \qquad (11)$$

and if T_λ is the gaseous transmittance:

$$\nabla\rho_\lambda{}^{sat} \approx T_\lambda\, \nabla\rho_\lambda^* \approx T_\lambda\, \nabla(\rho_g)\, e^{-\tau_\lambda(1/\mu_s + 1/\mu_v)} \qquad (12)$$

The ratio $R_\nabla(\lambda,\lambda_0)$ can be written:

$$R_\nabla(\lambda,\lambda_0) = \nabla\rho_\lambda / \nabla\rho_{\lambda 0} = \gamma_\lambda\, \nabla\rho_\lambda{}^{sat} / \gamma_{\lambda 0}\, \nabla\rho_{\lambda 0}{}^{sat}$$
$$= (\gamma_\lambda / \gamma_{\lambda 0})\, (T_\lambda / T_{\lambda 0})\, e^{-(\tau_\lambda - \tau_{\lambda 0})(1/\mu_s + 1/\mu_v)} \qquad (13)$$

The gaseous transmittance can be known with sufficient accuracy for all wavelengths except the 910 nm band for which absorption by water vapor plays a major role. As for the diffuse transmittance, the contributions of molecules and aerosols can be separated:

$$e^{(\tau_\lambda - \tau_{\lambda 0})(1/\mu_s + 1/\mu_v)} = e^{-(\tau_{m\lambda} - \tau_{m\lambda 0} + \tau_{a\lambda} - \tau_{a\lambda 0})(1/\mu_s + 1/\mu_v)} \qquad (14)$$

The spectral influence of the molecules on $R_\nabla(\lambda,\lambda_0)$ is known and can explicitely be accounted for:

$$\tau_{m\lambda} - \tau_{m\lambda 0} = 0.008\, (\lambda^{-4} - \lambda_0{}^{-4}) \qquad (15)$$

As for the aerosols, the spectral variation of the optical depth depends mostly upon the type of aerosol. If necessary, its correction will be examined.

The ability of the method proposed above to provide accurate enough interband calibration was analyzed by the means of a model of Laboratoire d'Optique Atmosphérique of Université de Lille.This model has already been used by Herman *et al.* (1991). It makes use of the successive orders of scattering to simulate the reflectance observed above the sea surface at satellite level, not taking into account the gaseous transmission. Simulations were done for various viewing angles, the sun zenith angle being set at about 40 degrees. Various aerosol loading and types were simulated, too. Only low wind speeds (2-5 m/s) were used. Model outputs confirm that this approach minimizes the role of the atmosphere and provides a spectrally constant quantity to calibrate each band relatively to the 490 nm reference band. Since the reflectance in the oxygen bands depends upon the pressure at the sea level under very clear skies, the exact value of the ratio requires the knowledge of this pressure which can be easily provided with a sufficient accuracy either by the meteorological data themselves or by one of the general circulation models. Thus all the spectral bands of PolDER, except 910 nm, can be calibrated relatively to 490 nm with an accuracy better than 1 %. As for 910 nm, the influence upon the ratio of the accuracy presently achieved in the retrieval of the water vapour content from meteorological data and the general circulation models should be examined.

CONCLUSION

It has been shown that a high accuracy interband calibration can be achieved by the means of the Earth viewing calibration approach which is the way CNES has selected for the in-flight calibration of the PolDER sensor.

REFERENCES

Abel, P., Report of the workshop on radiometric calibration of satellite sensors of reflected solar radiation, March 27-28, 1990, Camp Springs, Maryland. NOAA Technical Report NESDIS 55, 33 p., 1990.

Begni, G., Dinguirard, M. C., Jackson, R. D., and P. N. Slater, Absolute calibration of the SPOT-1 HRV cameras. *In* Proceedings SPIE 660, pp. 66-76, 1986.

Brest, C. L., and W. B. Rossow, Radiometric calibration and monitoring of NOAA AVHRR data for ISCCP. Submitted to *International Journal of Remote Sensing*, 1990.

Chou, M. D., The derivation of cloud parameters from satellite measured radiances for use in surface radiation calculations. *Journal of the Atmospheric Sciences*, **48**, 13, 1550-1559, 1991.

Frouin, R., and C. Gautier, Calibration of NOAA 7 AVHRR, GOES 5 and GOES 6 VISSR/VAS solar channels. *Remote Sensing of Environment*, **22**, 73-101, 1987.

Gu, X., Guyot, G., and M. Verbrugghe, Evaluation of measurement errors on the reflectance of "La Crau", the french SPOT calibration area. *In* Proceedings 10th EARSeL Symposium, pp 121-133, published by European association of remote sensing laboratories, 92108, Boulogne-Billancourt, France, 425 p., 1990.

Herman M., Deuzé, J. L., and P. Goloub, Inter-étalonnage des canaux PolDER. Utilisation du glitter. Convention CNES, rapport final, 19 p., Université de Lille, 1991.

Hill, J.V., Radiometric comparison and calibration of remotely sensed data from polar orbiting earth observation satellites. *In* Proceedings of the 5th Australasian Remote Sensing Conference, Vol. 1, 42-53, 1990.

Holben, B. N., Kaufman, Y. J., and J. D. Kendall, NOAA-11 visible and near-IR inflight calibration. *International Journal of Remote Sensing*, **11**, 8, 1511-1519, 1990.

Hovis, W. A., and J. S. Knoll, Aircraft measurements for calibration of an orbiting spacecraft sensor. *Applied Optics*, **24**, 145-160, 1985.

Justus, C. G., An operational procedure for calibrating and assessing the stability and accuracy of shortwave satellite sensors. Report of Georgia Institute of Technology, Atlanta, Georgia, USA, 99 p., 1989.

Justus, C. G., and M. V. Paris, Modeling solar spectral irradiance and radiance at the bottom and top of a cloudless atmosphere. Report of Georgia Institute of Technology, Atlanta, Georgia, USA, 99 p., 1987.

Kaufman, Y. J., and B. N. Holben, Calibration of the AVHRR visible and near-IR bands by atmospheric scattering, ocean glint and desert reflection. Submitted to *International Journal of Remote Sensing*, 1990.

King, M. D., Determination of the scaled optical thickness of clouds from reflected solar radiation measurements. *Journal of the Atmospheric Sciences*, **44**, 13, 1734-1751, 1987.

King, M. D., Radke, L. F., and P. V. Hobbs, Determination of the spectral absorption of solar radiation by marine stratocumulus clouds from airborne measurements within clouds. *Journal of the Atmospheric Sciences*, **47**, 7, 894-907, 1990.

Koepke, P., Vicarious satellite calibration in the solar spectral range by means of calculated radiances and its application to Meteosat. *Applied Optics*, **21**, 15, 2845-2854, 1982.

Koepke, P., Calibration of the VIS-channel of Meteosat 2. *Advances in Space Research*, **2**, 6, 93-96, 1983.

Martinuzzi, J.-M., Elements for the intercalibration plan of OCTS and PolDER. Report AP/OR/QTIS 451 of *Centre National d'Etudes Spatiales*, France, 62 p., 1991.

Nakajima, T., and M. D. King, Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part 1 : Theory. *Journal of the Atmospheric Sciences*, **47**, 15, 1878-1893, 1990.

Nakajima, T., King, M. D., Spinhirne, J. D., and L. F. Radke, Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part 2 : Marine stratocumulus observations. *Journal of the Atmospheric Sciences*, **48**, 5, 728-750, 1991.

Nann, S., and C. Riordan, Solar spectral irradiance under clear and cloudy skies : measurements and a semiempirical model. *Journal of Applied Meteorology*, **30**, 4, 448-462, 1991.

Paris, M. V., and C. J. Justus, A cloudy-sky radiative transfer model suitable for calibration of satellite sensors. *Remote Sensing of Environment*, **24**, 269-285, 1988.

Price, J. C., Radiometric calibration of satellite sensors in the visible and near infrared: history and outlook. *Remote Sensing of Environment*, **22**, 3-9, 1987.

Price, J. C., An update on visible and near infrared calibration of satellite instruments. *Remote Sensing of Environment*, **24**, 419-422, 1988.

Price, J. C., Calibration comparison for the Landsat 4 and 5 multispectral scanners and thematic mappers. *Applied Optics,* **28**, 465-471, 1989.

Santer, R., Asmami, M., and E. Vermote, Etalonnage des capteurs visibles de AVHRR. Convention EURATOM n° 3685.89.04 ED ISP S, Report of Laboratoire d'Optique Atmosphérique de l'Université de Lille, France, 84 p., 1990.

Saunders, R. W., An automated scheme for the removal of cloud contamination from AVHRR radiances over western Europe. *International Journal of Remote Sensing*, **7**, 7, 867-886, 1986.

Saunders, R. W., and K. T. Kriebel, An improved method for detecting clear sky and cloudy radiances from AVHRR data. *International Journal of Remote Sensing*, **9**, 1,123-150, 1988.

Smith, G. R., Levin, R. H., P. Abel, and H. Jacobowitz, Calibration of the solar bands of the NOAA-9 AVHRR using high altitude aircraft measurements. *Journal Atmosphere and Ocean Technology*, **5**, 631-639, 1988.

Tanré, D., Deroo, D., Duhaut, P., Herman, M., Morcrette, J.J., Perbos, J., and P.Y. Deschamps, Description of a computer code to simulate the satellite signal in the solar spectrum : the 5S code. *International Journal of Remote Sensing*, **11**, 4, 659-668, 1990.

Teillet, P. M., Slater, P. N., Mao, Y., Ding, Y., Yuan, B., Bartell, R. J., Biggar, S. F., Santer, R. P., Jackson, R. D., and M. S. Moran, Absolute calibration of the NOAA AVHRR sensors. *In* Recent advances in sensors, radiometry, and data processing for remote sensing, SPIE vol. 924, pp 196-207, Society of Photo-Optical Instrumentation Engineers, Bellingham, U.S.A., 1988.

Teillet, P. M., Slater, P. N., Ding, Y., Santer, R. P., Jackson, R. D., and M. S. Moran, Three methods for the absolute calibration of the NOAA AVHRR sensors in-flight. *Remote Sensing of Environment*, **31**, 105-120, 1990.

Wald, L., Elaboration d'un algorithme de décontamination des nuages sur une série pentadaire d'images de capteur grand champ. Convention de recherche 833/CNES/89/6078, rapport final CTAMN/91/R/02. Ecole des Mines de Paris, France, 120 p., 1991.

Wald, L., and Monget J.-M., Sea surface winds from sun glitter observations *Journal of Geophysical Research*, **88**, C4, 2547-2555, 1983.

Wald, L., Sèze, G., and M. Desbois, Automatic cloud screening in NOAA-AVHRR day-time imagery. *In* Proceedings of the fifth AVHRR data users meeting, pp. 89-94, Eumetsat ed., EUM-P-09, 490p., 1991.

Wetzel, M. A., and T. H. Vonder Haar, Theoretical development and sensitivity tests of a stratus cloud droplet size retrieval method for AVHRR-K/L/M. *Remote Sensing of Environment*, **36**, 105-119, 1991.